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A Review of the Bulk-Loaded Liquid Propellant Gun Program for Possible Relevance to the Electrothermal Chemical Propulsion Program

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Some findings from the phenomenological studies during the earlier bulk-loaded liquid propellant gun programs are reviewed for possible relevance to the electrothermal chemical (ETC) propulsion program. The review includes studies on the basic combustion mechanism, conditions that resulted in relatively flat pressure-time profiles, and conditions that may have contributed to catastrophic failures. The studies on the basic combustion mechanisms concluded that the hydrodynamic instabilities occurring during the interior ballistic cycle are sufficient to break-up the charge and result in complete combustion during the interior ballistic cycle. The dominant instabilities include the penetration of a gas cavity into the liquid propellant, called a Taylor cavity; and the rapid liquid break-up due to mixing at the gas liquid interface, referred to as Helmholtz mixing. The initial conditions are also summarized for tests which resulted in relatively flat pressure-time traces. For relevance to the electrothermal chemical program, it is concluded that proper control of the initial conditions will likely be critical for establishing a reasonable level of repeatability.

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PREFACE

On 30 September 1992, the U.S. Army Ballistic Research Laboratory (BRL) was deactivated and subsequently became part of the U.S. Army Research Laboratory (ARL) on 1 October 1992.

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1. INTRODUCTION

Charge designers use a variety of chemical and physical means to control the interior ballistic (IB) process. In the case of solid propellant guns, for instance, propellant type, granulation, web and mode of ignition are among the control mechanisms used to attain reliable, repeatable interior ballistics. Although specific control factors depend upon the physical mechanisms of any given propulsion scheme (Juhasz, Knapton, and White 1990), the principles used to govern widely differing IB processes are similar. The concern for avoiding pressure waves (e.g., the distributed ignition principle used in solid propellant charges) was also considered in bulk-loaded liquid propellant (BLP) gun systems.

Currently, there is strong interest in electrothermal-chemical (ETC) gun propulsion. In this approach, a bulk of energetic working fluid is ignited by an injected plasma resulting in the gas generation needed to cause projectile motion. This process is, in some ways, similar to the ignition of a BLP charge. Considering this similarity, as well as the potential commonality of principles governing the functioning of widely differing gun systems, it is possible that some of the control factors found to work for BLP guns might also apply as well for ETC guns.

The objective of this report, therefore, is to bring together a number of observations made on the control of the BLP gun over a 30–40 year period in the hopes that the observations will prove useful to investigators currently engaged in the ETC gun area. Obviously, the summary given in this report cannot be comprehensive due to the extensive number of BLP gun studies. What we will present is a summary of the major control mechanisms together with some illustrations. A more complete summary of the experimental control mechanisms used in BLP guns may be found in Knapton et al. (to be published).

2. COMBUSTION MECHANISMS IN BLP GUNS

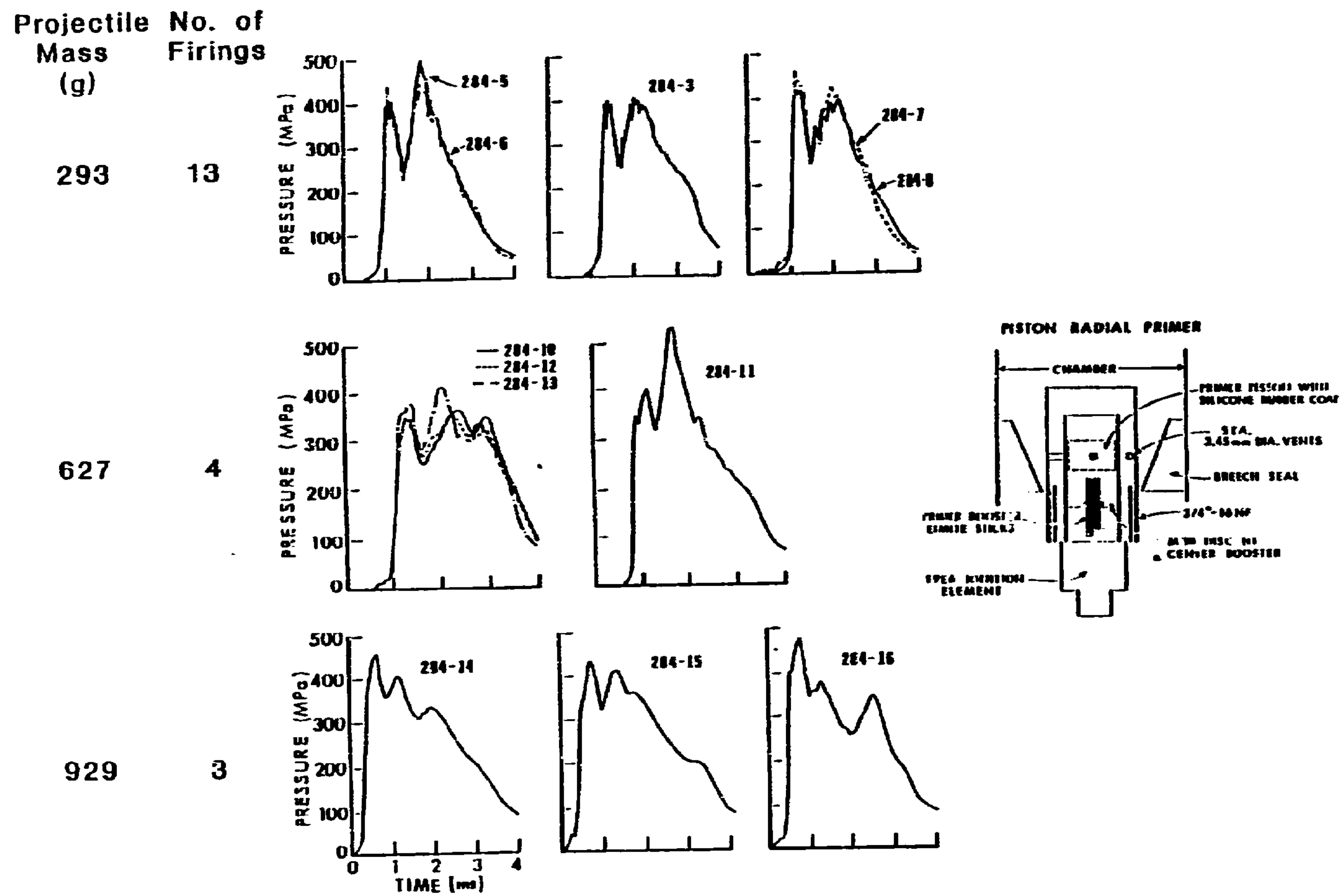
The combustion mechanisms in BLP guns are reviewed elsewhere (Knapton et al., to be published; Comer, Shearer, and Jones 1963; Comer and McBratney 1972; Comer 1977; Guzdar, Rhee, and Erickson 1971; Phillips et al. 1980; Morrison, Knapton, and Bulman 1988). Here we will give only a brief summary of the dominant combustion mechanisms which are believed to exist during the IB cycle.

First, for a comparison, the gas generation rate for solid propellant guns is accurately given by the known dimensions of the solid propellant grains and the linear burning rate. For the BLP gun there is no well-defined surface which can be used to estimate the gas generation rate. Instead, the gas generation rate requires various hydrodynamic instabilities to generate the required pressure during the IB process. Numerous experimental BLP gun programs have shown that the best performance can be achieved with breech ignition, although some studies have suggested that ignition at the base of the projectile may give better repeatability. Because of interest in increased performance, however, most of the studies have involved pyrotechnic or electrical ignition at the breech. With breech ignition, both a pressure wave and a gas cavity are formed. The important effects of pressure waves are considered only briefly in this report; the effect of pressure waves are examined more thoroughly in a separate paper (Knapton and Minor 1990).

The gas cavity is referred to as the "Taylor cavity." As the projectile is accelerated down bore, the Taylor cavity penetrates through the liquid column, a result which occurs when any two-fluid system is accelerated such that the less dense fluid (the gas) is accelerated in the direction of the more dense fluid (the liquid propellant). A gas core is formed along with a turbulent gas-liquid interface. The gas-liquid mixing at this interface is called "Helmholtz mixing" and is the dominant combustion mechanism during the IB process.

The growth of the Taylor cavity is dependent on the acceleration of the projectile, and the Helmholtz mixing is dependent on the gas velocity at the gas-liquid interface. Therefore, the development of the required propellant surface area during the IB process is dependent on functions related to velocity and acceleration. One might expect, therefore, that the gas evolution would be dependent on the inertia of the propulsion system (i.e., the mass of the projectile and the charge). Tests in a 37-mm gun were performed (Comer, Shearer, and Jones 1963) without damage to the gun with hydrazine-based monopropellants with projectile masses varying by a factor of 50 (from 71 g to 3.63 kg). Also, tests were performed (Knapton et al. 1983; Knapton and Stobie 1979b) in a 37-mm gun with a HAN-based monopropellant (NOS-365) with the same charge mass and with projectile masses varying from 293 g to 929 g, also without excessive pressures. The pressure-time records from the tests with the HAN-based monopropellants are shown in Figure 1. These examples serve to

Bulk Loaded Liquid Propellant Gun Tests
Effect of Projectile Mass



Source: Knapton et al. 1983; Knapton and Stobie 1979b.

Figure 1. Examples showing effect of projectile mass on pressure-time curves for a 37-mm BLP gun.

illustrate the importance of the acceleration and velocity on controlling the generation of the propellant surface area and thereby limiting the gas evolution.

With an understanding of the combustion mechanisms one can recognize the importance of breech ignition in establishing the Taylor cavity and the subsequent Helmholtz mixing. With ignition elsewhere in the charge (e.g., at the projectile base), there would likely be a pressure profile established in the charge which would disturb the propagation of the Taylor cavity and retard the gas generation rate and result in reduced performance. For those cases where ignition at the projectile base yielded reasonable performance, it was never clear if there was, indeed, secondary ignition at the breech as a result of adiabatic compression of gas bubbles. This uncertainty on the existence of possible uncontrolled ignition sites serves to emphasize the importance of using extensive diagnostics during the development stages in exploratory propulsion programs.

Although many bulk-loaded studies relied on breech ignition, the studies were performed at the expense of exacerbating the longitudinal pressure wave problem. Therefore, the studies (Knapton and Minor 1990) frequently included investigations of various techniques, such as the use of foam and projectile base wave absorbers, to minimize pressure wave reinforcement effects.

3. CONTROL MECHANISMS AND IGNITION SOURCES IN THE BLP GUN

The IB control mechanisms that have been evaluated for the BLP gun are the mechanisms related to the initial conditions: igniter characteristics, propellant properties, ullage, and chamber geometry. Details on these initial conditions may be found in Knapton et al. (to be published). For a dynamically injected propellant, such as what might be used in a practical weapon, an additional control mechanism exists related to the injection parameters and the subsequent emulsion (droplet size and distribution) in the chamber (Wood and Bryant 1977; Charters, Compton, and Wood 1977; Mallory 1981, 1984). Once the ignition of the charge and combustion are underway, the mass generation rate of gas depends on the fluid dynamic instabilities discussed above. An additional instability mechanism, ignition from adiabatic compression of bubbles, may also occur with some propellants. If adiabatic compression of bubbles is likely, then a potentially serious problem may exist due to ignition

throughout the charge and the generation of excessive gas generation rates. A further uncontrolled ignition source may also occur as a result of frictional heating and ignition during the engraving process.

In order to introduce some control during combustion, Goddard and Goddard (1983, 1984) (Goddard 1981) proposed the use of what they called non-Newtonian controlled burning surface propellants (e.g., gelled propellants). The type of propellants envisioned included propellants with physical properties that would dampen instability waves during combustion and propellants containing solids that would offer a well-defined surface area. The proposed approach has merit and will be commented on in a subsequent section.

4. EXAMPLES OF FLAT PRESSURE-TIME CURVES

To provide some illustrations of the type of IB control which investigators have identified, we summarize in this section examples where conditions were such that relatively flat chamber pressure vs. time curves were generated. Flat pressure-time curves have been a goal of interior ballisticians for many years. Maximum performance is obtained when the projectile base pressure is constant throughout the projectile travel. Since the base pressure in not usually measured, we report here the chamber or breech pressure which is often used, assuming the Lagrange density distribution, as an indication of the base pressure.

4.1 <u>30-mm, Detroit Controls Corporation</u>. During the 1950s, Elmore, Quinn, and Anderson (1955) performed many parametric tests with a mixture of hydrazine, hydrazine nitrate, and water in a 30-mm gun. For a 62.4%, 31.7%, and 5.7% mixture, they found for both pyrotechnic and electrical ignition that the location of the igniter in the chamber and the angle at which the gases vented into the chamber were important parameters, and that in some cases, reasonably flat pressure-time curves were generated. It was found that venting the gases tangentially into the chamber, when compared with a radially venting primer, gave the most satisfactory performance.

Based on the pressure-time traces given in Elmore, Quinn, and Anderson (1955), it appeared that the radially venting primer gave somewhat better flat pressure-time curves. Interestingly, there was little difference in the performance for either rear or front ignition;

better repeatability was obtained when the igniter was located at the base of the projectile. These observations, when compared with the later work of Jones et al. (1965), suggest that additional ignition sites may have indeed been present. Normally, as indicated earlier, the performance would be expected to be degraded if ignition is limited to ignition at the projectile base.

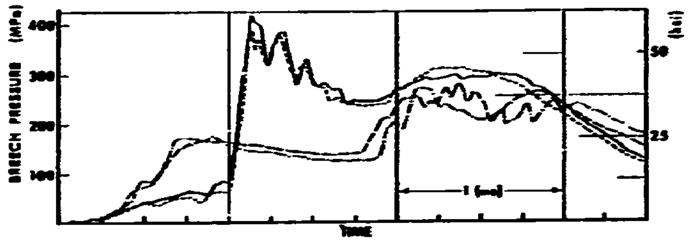
The tests with the tangentially vented igniter suggest that some improvement in the control of the IB processes may result if there is some initial stability as a result of centrifugal forces imparted to the initial formation of the Taylor cavity. This possible control mechanism was not studied further with the exception of some promising unpublished results reported more recently by R. Pate (1989).

Elmore, Quinn, and Anderson (1955) also found that the propellant properties could have a significant effect on the type of pressure-time traces. The hydrazine nitrate content was varied from 23% to 42% while keeping the water content at 5%. Interestingly, for tests with 32% hydrazine nitrate content, the pressure-time traces were relatively flat.

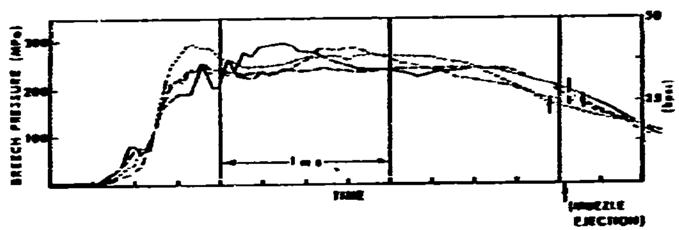
4.2 37-mm, Ballistic Research Laboratory (BRL).* Comer, Shearer, and Jones (1963), in the report mentioned earlier, and Jones et al. (1965) in the 1950s and early 1960s, reviewed a large body of data obtained from both Otto-II and hydrazine firings in 37-mm guns. They concluded that the data could be divided into two groups based on the shape of the acceleration-time curve and, to a lesser extent, on the shape of the pressure-time curve. The data included tests where the muzzle velocities varied from 424 to 2,589 m/s, depending on the charge-to-mass ratio and the expansion ratio. They (Jones et al. 1965) concluded from their diagnostic tests that, in the first group, the propellant was probably ignited at the projectile base and burned mainly in the chamber; and, in the second group, some of the propellant was displaced down bore before being converted to gas. The resulting pressure-time curves for the first group of tests were mostly flat (Figure 2b). The second

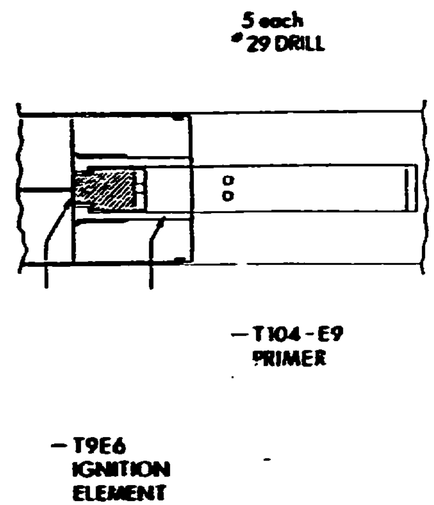
*On 30 September 1992, the U.S. Army Ballistic Research Laboratory was deactivated and subsequently became a part of the U.S. Army Research Laboratory on 1 October 1992.

a) Breech ignition with postulated down tube burning breech pressures for highest and lowest pressures



b) Breech ignition with postulated projectile base ignition; burning mainly in chamber.





PROPELLANT: HYDRAZINE (65%), HYDRAZINE NITRATE (30%), WATER (5%)
PRIMER 5 HOLE RADIAL VENT, M38B2 IGNITER ELEMENT WITH BOOSTER CHARGE IN
BAYONET TYPE PRIMER.
SAMPLE SIZE 29
BREECH PRESSURE SUMMARY:
FIRST PEAK (P_1) = 247 MPa, σ = 76.4 MPa (31%)
SECOND PEAK (P_2) = 280 MPa, σ = 24.5 MPa (8.7%)

Source: Comer, Shearer, and Jones 1963.

Figure 2. Example of variabilities in pressure-time traces recorded in a 37-mm BLP gun, hydrazine-based LP.

group resulted in two peaked-type pressure curves (Figure 2a). Also, the second group resulted in higher projectile velocities, but at the same time a higher variability in the results. Their conclusions (Jones et al. 1965) on likely front end ignition were arrived at from tests using bore surface thermocouples to detect onset of burning and tests with water barriers at the base of the projectile to prevent the suspected propellant ignition during projectile engraving. As a result of their diagnostics, they postulated that ignition of the charge occurred during engraving for the first group of tests.

During the 1960s, McBratney (Comer and McBratney 1972; McBratney, unpublished; Knapton et al. 1977) studied spark ignition using a hydrazine-based monopropellant in a 37-mm gun. The igniter was located in the breech in a cylindrical cavity or spark plenum with an insulated center electrode. A capacitor discharge caused electric current to flow through the propellant located between the electrodes. The capacitance was 30 µF and the voltage applied across the capacitor was about 1,800 V. For a group of seven rounds with a projectile mass of 146 g and a charge-to-mass ratio of about 2.24, the mean muzzle velocity was 2,088 m/s with a standard deviation of 2.1%. The pressure time curves showed a rise to a peak pressure followed by a relatively flat plateau.

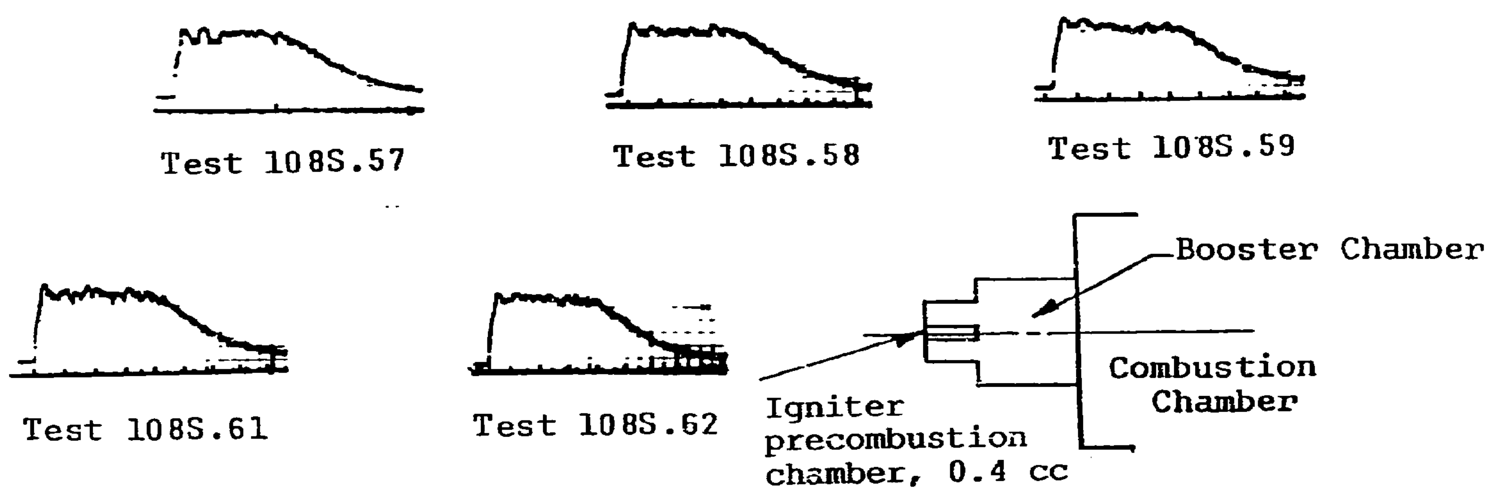
4.3 90-mm, Detroit Controls Corporation. In the 1950s, Elmore (1975) tested various hydrazine mixtures in a 90-mm tank gun. The propellant was ignited at the breech using a spark discharge in a 0.4-cm^3 pre-combustion chamber followed by a 2.5-cm^3 booster chamber. The pressure-time traces were generally flat, especially for tests with a mixture of 63% hydrazine, 32% hydrazine nitrate, and 5% water. Figure 3 shows a group of five rounds. For one group of five tests with a charge-to-mass ratio of 1.06, the mean maximum chamber pressure was 379 MPa with a variation in the standard deviation of 1.8%. The corresponding mean velocity was 1,423 m/s with a variation in the standard deviation of 0.86%.

4.4 120-mm, Ballistic Research Laboratory. McBratney (Comer and McBratney 1972a; Knapton et al. 1977; McBratney 1964–1967), also in the mid to late 1960s, performed tests using a hydrazine mixture in a 120-mm gun with a 12.24-liter chamber. A total of 29 firings were made with the objective of demonstrating the high performance capability of the BLP gun in a large-caliber weapon. The propellant was a mixture of hydrazine and hydrazine nitrate, and the ignition was at the breech. The primer was pyrotechnic and was tested with various

Example of Flat Pressure - Traces
Detroit Controls Corporation

Caliber: 90-mm, T228 gun
Propellant: Hydrazine 63%, Hydrazine Nitrate 32%, Water 5%
Projectile Mass = 5.67 kg
C/M = 1.06
Igniter: Electrical ignition with 0.4 cc precombustion chamber followed by 2.5 cc booster chamber.
No. of Tests: 5

P MPa	std dev (%)	V m/s	std dev (%)
379	2.0	1423	0.86



Source: Elmore 1975.

Figure 3. Examples of breech pressures from a 90-mm BLP gun, hydrazine-based LP.

vent patterns and primer mixes. The test series demonstrated that a relatively flat breech pressure-time trace could be generated. The maximum performance for a 3.57-kg projectile with a charge-to-mass ratio of 3.53 and 50.8 calibers of travel was 2,140 m/s. For this test the maximum breech pressure was 328 MPa. The chamber length from the breech face to the projectile base was 647 mm.

An illustration of the primer used in one of the tests along with the pressure-time curves is shown in Figure 4. The primer charge consisted of 13.4 g of A4 black powder, 2.0 g of Fe_2O_3, and aluminum foil to seal the holes. The internal volume of the primer was 18.6 cm^3. Earlier tests had suggested that the addition of the Fe_2O_3 yielded improved ignition. To reduce the possibility of front end ignition during the engraving process, a nylon engraving band was used. Test Nos. 24–28 also resulted in acceptable ignition and pressure-time data. On Test No. 29, the tube failed—apparently a result of poor ignition. Likely cause for the failure is given in the following section.

5. CATASTROPHIC FAILURES

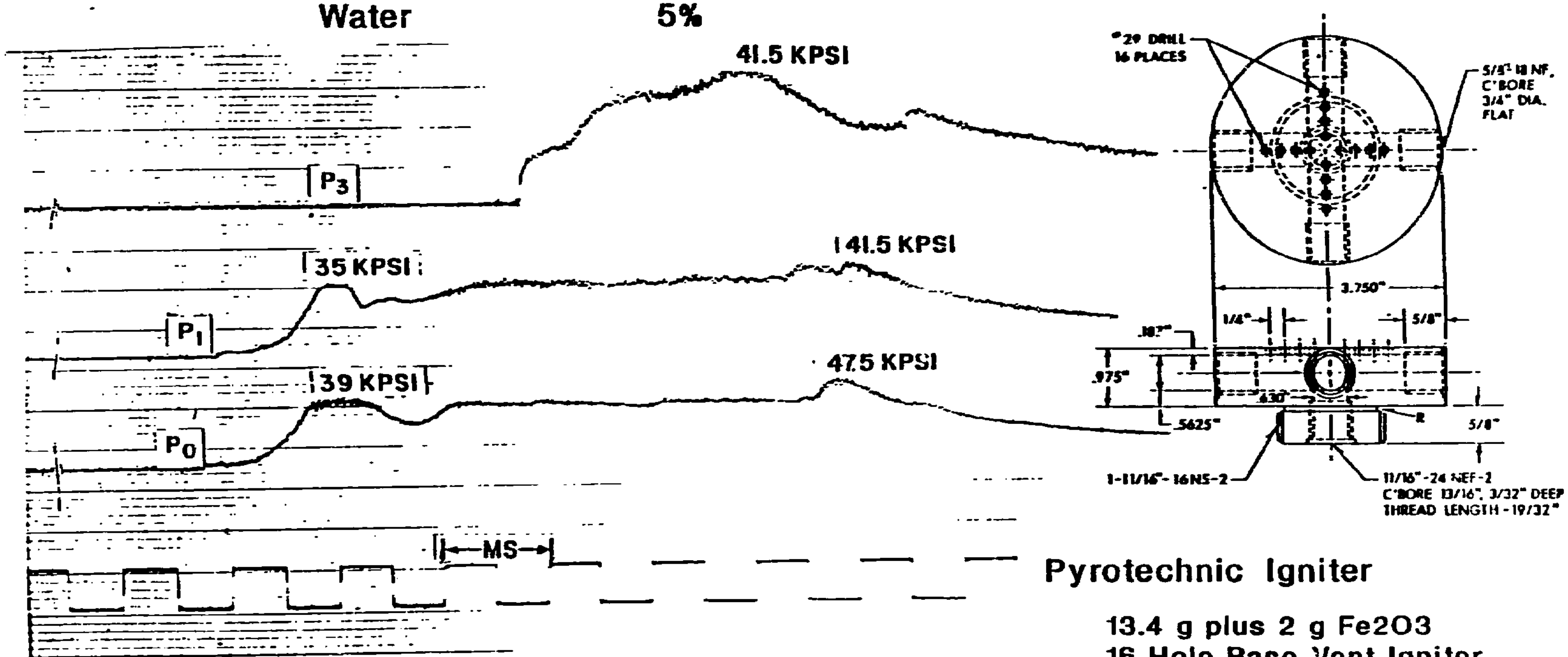
The studies on the initial conditions which offered a level of control of the IB processes resulted in many successful programs. Because of the velocity and acceleration-dependent mechanisms discussed earlier, it may first appear that excessive pressures should be automatically avoided in BLP guns. Unfortunately, such is not the case. Several catastrophic failures occurred during the BLP gun test programs. We review in this section the conditions which likely contributed to the failures. Importantly, these same conditions, depending to a large extent on the type of propellant, may also apply to ETC guns.

Conditions contributing to high pressures are likely a result of poor ignition and/or conditions which may contribute to the generation of a large surface area of the propellant. Related conditions which can further exacerbate the evolution of excessive gas generation involve the high initial loading density in the chamber; the lack of dissipative mechanisms for wave attenuation, such as boundaries which exist at solid propellant grains; uncontrolled ignition sites, such as ignition from adiabatic compression of bubbles; and the basic hydrodynamic instability mechanisms.

Bulk Loaded Liquid Propellant Gun; Pressure-Time

Example of Analog Data. Round No.23

Caliber: 120-mm
Projectile Mass = 3.57 kg Velocity = 2140 m/s
C/M = 3.53
Propellant: Hydrazine 65%
Hydrazine Nitrate 30%
Water 5%



Pyrotechnic Igniter

13.4 g plus 2 g Fe2O3
16 Hole Base Vent Igniter
Internal Volume = 19.7 cc

W.F.McBratney, Unpublished BRL Firing Records, Sep 66 - Mar 67

Source: Comer and McBratney 1972a; Knapton et al. 1977; McBratney 1964–1967.

Figure 4. Examples of breech pressures from a 120-mm BLP gun, hydrazine-based LP.

5.1 120-mm, Ballistic Research Laboratory. The last firing in the 120-mm BLP gun firing series resulted in a catastrophic failure. The failure was attributed to poor ignition. Based on a post-firing review, it appeared that the gases from the igniter had vented to the rear of the primer as well as into the propellant. The result was a poorly ignited charge resulting in displacement of the charge down bore and a large increase in the propellant surface area. The unburned propellant, combined with a large surface area, ignited in a region of the gun tube which could not withstand the resulting pressure.

5.2 25-mm Dynamically Loaded BLP Gun, Naval Weapons Center (NWC). The NWC (Wood and Bryant 1977; Charters, Compton, and Wood 1977; Mallory 1981, 1984) developed a bipropellant, automatic 25-mm BLP gun designed to operate at a firing rate of 350 rounds/min. The bipropellant was a mixture of 90% nitric acid and a proprietary hydrocarbon. From the NWC technology studies, it was concluded that the injector design and operating characteristics provided an important method for controlling the ballistics. Either high or low pressures could be generated, depending on the injection parameters. High pressure resulted when the injected fuel had a surface-to-volume ratio of 119/cm, while low pressures resulted when the surface-to-volume ratio was 39/cm. It was found that the gun operated satisfactorily with a surface-to-volume ratio between 39–59/cm. Variations in the oxidizer-to-fuel ratio could also be used to change performance. The effect of ullage, for small values of 3–5%, was found to be important for ignition and functioning of the gun, but had little effect on the ballistics.

A catastrophic failure occurred during the early testing and was attributed to, too fine of a mix as a result of the injector characteristics.

5.3 75-mm, Pulsepower Systems Incorporated (PSI). PSI studied (Quinn and Boyd 1978) under a DARPA contract the technology for developing a high performance, automatic 75-mm BLP Gun. Monopropellant NOS-365 was used in the tests and the propellant was electrically ignited. Two successive failures occurred—Round No. 205 (June 1976) and Round No. 206 (5 August 1976). For Round No. 205, stored electrical energy amounting to 288 J (Elmore 1976a) was used. The charge-to-mass ratio was 1.0, the chamber volume was 2032 cm^2, and the estimated ullage was 32.9 cm^2. The initial evaluation of the results from Round

No. 205 was that a high-order detonation may have occurred near the middle of the chamber at about 45.7 cm.

Continued review studies on the results from Round No. 205 by B. Taylor, BRL, Drabo and R. Huddleston, Material Test Directorate (MTD), Aberdeen Proving Ground, MD, concluded (Knapton 1976a) that there was not sufficient evidence to warrant a definite finding that there was a high-order detonation. Examination of the metal fragments suggested that the damage could have been caused by a single event or by a number of earlier firings. Further, the Rockwell hardness numbers indicated that the steel was extremely brittle as a result of poor heat treatment. It was concluded that a possible metallurgical problem may also have been a contributing factor to the failure associated with Round No. 205.

Supporting the possibility that the gun tube was already damaged prior to Round No. 205, was the result from Round No. 204. Based on a conference telephone call between MTD, BRL, and NWC, it was indicated that the chamber after Round No. 204 had been deformed by 80 mil due to high chamber pressure in the round (Knapton 1976b). It was also concluded from this conversation that there were sufficient questions as to preclude a firm conclusion that a high-order detonation had indeed occurred during Round No. 205.

The pressure-time trace from Round No. 206 (Comer 1976) indicated an initial pressure rise to about 20 ksi within about 250 μs which was followed by a "... rapid decay to about 4–5 ksi all within about 250 μs. This low pressure regime continued about 500–600 μs after the initiating sparking event, and then this round also appeared to go as a high-velocity detonation." At this time, the cause of the explosion (Incl 1 to Comer [1976]), despite earlier negative results from the Naval Ordinance Laboratory (NOL) card gap test, appeared to be a result of shock initiation of a low-order detonation in a non-homogeneous (bubbly) liquid monopropellant which transited to a high-order detonation under confinement (Fourth International Symposium 1965).

Our conclusions from a review of the evidence, is that the high pressures were likely due to combustion, possibly a low order detonation. The cause of the high pressures for the two firings was never studied in detail. Our conclusions as to the cause of the high pressures

were likely associated with a procedural loading and firing error for Round No. 205, possibly coupled with an abnormal propellant.

The procedural error resulted in the propellant being rapidly loaded and fired without the normal propellant pre-pressurization. The measured pre-pressurization (Quinn and Boyd 1978) was less than 115 psi, which compared with a normal pre-pressurization of 800 psi. As a result, there were likely large bubbles distributed throughout the charge which may have ignited from adiabatic compression during ignition. The abnormal propellant may have been due to a mixture of propellants, including one lot (H-38) which was shown later to be difficult to ignite (Elmore 1976b).

Another possible cause of the failure may have been associated with adiabatic compression of trapped gas during the ignition. The trapped gas, located at the projectile base, may have been due to the low pre-pressurization which resulted in an improperly seated projectile.

A possible contributing factor to the high pressure recorded in Round No. 206 was likely the abnormal propellant, lot H-38. As described previously, the pressure start-up characteristics showed an abnormal long delay from 500 to 600 µs at relatively low pressure.

6. IGNITION CONSIDERATIONS

For possible relevance to ETC, a summary of the ignition energies may be of interest. Solid or liquid propellants may be ignited with less than 1 J of energy. For practical igniters for use in guns, considerably more energy is required if the ignition is to result in sustained combustion and complete burning of the charge. Table 1 gives an estimate of the ignition energies that have been successfully applied in various test programs. Location of the igniter is limited to breech ignition, although similar levels of energies were used in programs where the location of the igniter was changed.

Two energies are listed in Table 1 for the cases with the electrical igniters. The first number refers to the electrical energy based on what was believed to have been delivered to

Table 1. Summary of Ignition Energies Used in Various BLP Gun Programs

Gun	Propellant	Type of Ignition	Charge (kg)	C/M	Estimate of Igniter Energy (kJ)	Velocity (m/s)	Reference
30-mm	Hydrazine	electrical	0.075	0.360	0.096, 4.2	989	Elmore[a]
37-mm	Hydrazine	electrical	0.329	2.240	?, 4.8	2088	McBratney[b]
90-mm	Hydrazine	electrical	6.010	1.060	?, 1.5	1423	Elmore[c]
120-mm	Hydrazine	pyrotechnic	12.600	3.530	1.3	2140	McBratney[d]
30-mm	NOS-365	electrical	0.208	1.320	0.020, 3.2	—	Fisher[e]
37-mm	NOS-365	pyrotechnic	0.362	1.120	2.4	1531	Stobie[f]
37-mm	NOS-365	solid propellant	0.268	0.843	100	1453	Stobie[g]
73-mm	NOS-365	electrical	2.800	1.340	0.3, 1.7	—	Elmore[h]

[a] Elmore, Quinn, and Anderson 1958
[b] McBratney, unpublished; Knapton et al. 1977
[c] Elmore 1975
[d] Knapton et al. 1977; McBratney 1964–1967
[e] Fisher and Sterbutzel 1976
[f] Knapton et al. 1983; Knapton et al. 1978
[g] Knapton et al. 1983; Knapton and Stobie 1979b
[h] Quinn and Boyd 1978; Elmore 1976a

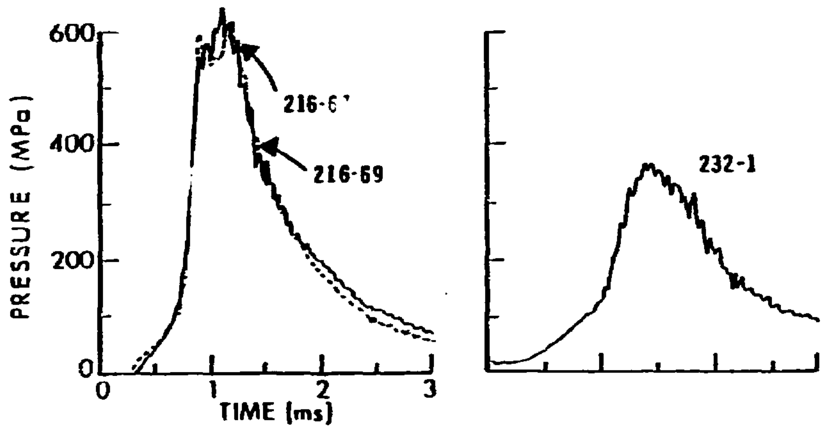
the electrodes, and the second number refers to the energy of the propellant contained in a pre-combustor volume adjacent to the electrodes.

Aside from the 37-mm example which used a relatively large solid propellant igniter, Table 1 shows that the ignition energy is quite small when compared with energies normally used for ETC application.

Perhaps one of the more interesting examples in Table 1, which may be of relevance to ETC, is the 37-mm example with the large solid propellant igniter. In this case, the ignition energy begins to approach the electrical energy used for medium-caliber ETC guns. The pressure-time record for this example is illustrated in the center figure in Figure 5. With a large solid propellant igniter, the control of the initial start-up characteristics should be improved. These tests were performed at the end of the last BLP program and only a few tests were conducted. The examples shown in Figure 5, however, suggest that if control of the start-up is achieved, then perhaps improved repeatability can be obtained as well as an approach for controlling the maximum pressure.

Repeatable ignition (Knapton and Stobie 1979a) has been considered a necessary condition for achieving repeatable ballistics. Unfortunately, for the BLP gun, there are other conditions which must be considered. One of the more disturbing comparisons from some 37-mm tests is shown in Figure 6. Prior to this firing, the igniter had been evaluated (Knapton et al. 1983) in open air tests and in closed chamber tests. In these tests, it was found that the igniter offered an approach for achieving repeatable performance. When tested in a 37-mm gun, the pressure-time curves confirmed (as shown by the example in Figure 6) that there was excellent agreement in the pressure-time curves for two tests during the early start-up. However, later in the IB cycle, the two pressure-time curves deviated markedly. The deviation illustrated in the two records in Figure 6 occurs where the Helmholtz mixing would be expected to dominant the IB process. Therefore, it appears that additional control mechanisms are necessary if the BLP gun is to function in a repeatable manner. Of course, one method postulated by the ETC community for achieving control is to maintain the electrical input over a longer period of time.

Bulk Loaded Liquid Propellant Gun Tests
Hybrid Charge

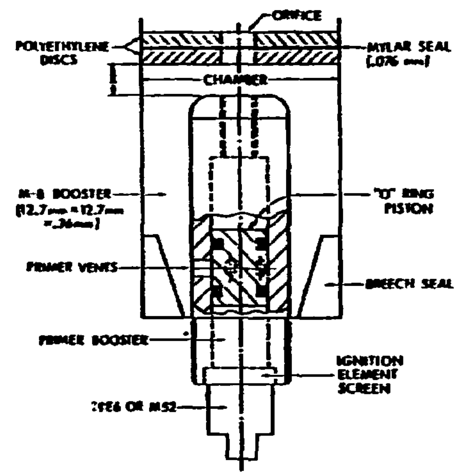


IGNITER: 505 mg U
14.8 g M8

IGNITER: 330 mg U
24.5 g M8

GUN: 38.8 mm
PROPELLANT: NOS 365
PROJECTILE: 318g

IDENT NO	CHARGE (g)	EXPANSION RATIO	VELOCITY (m/s)
216 - 67	290	15.4	1514
216 - 69	272	16.4	1503
232 - 1	268	16.6	1453



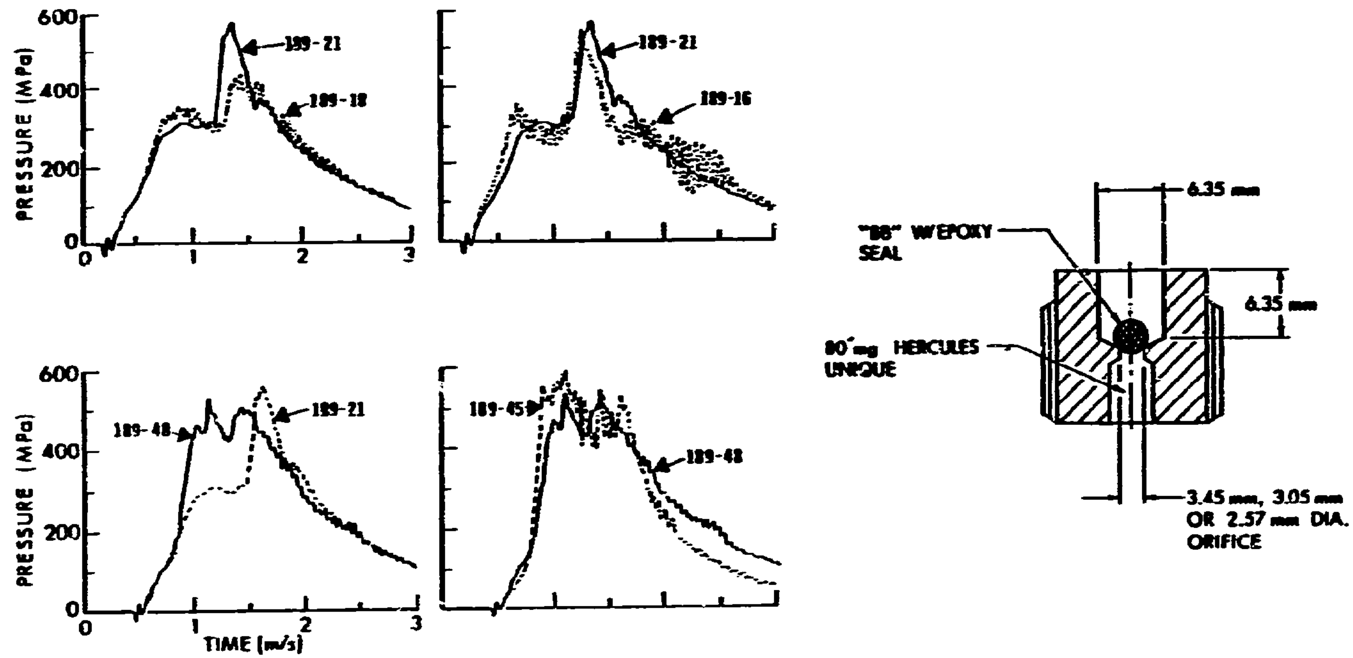
IDENT	PRIMER MODEL	BOOSTER MASS (g)	X (MM)	INITIATOR	ORIFICE DIA (MM)
216-67	PMk2	14.06	6.4	M-52	12.7
216-69	PMk2	14.06	6.4	T9E6	12.7
232-1	PMk1	24.48	19.1	T9E6	6.4

"O"-Ring Piston Radial Primer

Source: Knapton et al. 1983; Knapton and Stobie 1979b.

Figure 5. Example of possible control of the breech pressure-time history by use of a large solid propellant igniter.

Bulk Loaded Liquid Propellant Gun Tests
Axial Ignition



GUN: 38.8 mm
IGNITER: END VENT PRIMER WITH UNIQUE POWDER
PROPELLANT: NOS 365
CHARGE: 363 g
PROJECTILE MASS: 318 g
EXPANSION RATIO: 12.5
NUMBER OF FIRINGS: 5

$\overline{P1}$ = 419 MPa (σ = 28%)
$\overline{P2}$ = 530 MPa (σ = 10%)
$\overline{V1}$ = 1566 m/s (σ = 2.5%)

Primer developed by W.McBratney, BRL

Source: Knapton et al. 1983; Knapton and Stobie 1979b.

Figure 6. Examples of chamber pressures showing repeatable pressure-time start-up, but lack of repeatability at maximum pressure. The propellant was a HAN-based LP.

7. DISCUSSION

We have not summarized in this report the level of reproducibility that might be achieved with the BLP gun. Appropriate summaries are given elsewhere (Morrison, Knapton, and Comer 1976) and generally show that the best that can be expected for muzzle velocity repeatability, based on small groups of data, is a one standard deviation between 1.0 and 1.5%.

The necessary and sufficient conditions (Comer, Shearer, and Jones 1963; Comer 1977) to achieve complete burning of a BLP charge during an IB cycle may be obtained from the fluid dynamic mechanisms associated with the Taylor cavity and Helmholtz mixing. Both of these mechanisms represent instabilities and, therefore, the predictive capability on how the charge breaks up and burns has not been predicted with any reasonable level of confidence. The lack of a predictive capability has been one of the reasons which has limited the technology development of the BLP gun. This limitation was recognized in the 1950s, and pointed out in a review paper by Lewis et al. (1955). They concluded that the empirical design procedures for shaping the pressure-time curves do not permit the use of scaling methods for application to the design of large-caliber guns. What is required is a fundamental analysis of the combustion coupled with the hydrodynamic processes. Although several hydrodynamic models were later formulated for the BLP gun, there were no models that were validated against experimental data.

Although we have concentrated in this review primarily on the conditions which resulted in flat pressure-time curves, it is apparent from a review of the many BLP gun programs that the BLP concept offers a means of generating most any type of pressure-time curve. Conditions which might offer some control on the shape of the pressure-time curve include the type of igniter (i.e., radial vent vs. axial vent); a tangentially vented primer as discussed earlier (Elmore, Quinn, and Anderson 1955); the increased igniter energy approach demonstrated by Knapton et al. (1983) and Knapton and Stobie (1979b); propellant properties; ullage; and chamber configuration (Knapton et al. 1983; Knapton and Stobie 1979b; Elmore 1976b; McBratney 1981). This report has touched only briefly on these techniques. The chamber configuration was also found to be an important method for controlling the maximum chamber pressure (Knapton et al. 1983; Knapton and Stobie 1979b; McBratney 1981), as well as

various projectile base wave absorbers (Comer, Shearer, and Jones 1963; Knapton et al. 1983, Knapton and Stobie 1979; DeDapper 1959).

The results from PSI (Quinn and Boyd 1978; Elmore 1976a, 1976b) demonstrate that propellant characterization tests are necessary prior to firing the propellant in guns. Tests should include analytical composition, sensitivity tests, and ignition and combustion tests. The identification of a suitable test fixture to qualify the propellant for gun testing was never established. The only test which suggested a possible problem with the lot of propellant tested at PSI were the actual test firings in a 25-mm electrically ignited fixture.

Although the IB gas evolution process, based on tests covering a wide range of projectile masses, appears to be largely self-limiting, it must be emphasized that this effect is not independent of the propellant, the type of igniter, and the charge configuration.

It appears that two of the catastrophic failures described above may be attributed to improper ignition of the propellant. Interestingly, Lamonica and Hedden (1955), based on tests with hydrazine nitrate in 40-mm cased rounds, commented on such a problem 35 years ago:

> ".... It was discovered that high chamber pressures may result if the igniter does not supply sufficient energy to the propellant to immediately initiate the main self-sustaining reaction before some motion of the projectile takes place. The mechanism operating in such cases would seem to be that the igniter produces at first only a feeble propellant reaction, but that sufficient pressure is produced to initiate motion of the projectile. This motion of the projectile increases .... the volume available to the propellant and a vigorous reaction takes place in a chamber in which, in effect, the ullage has been increased to a high value. Pressures characteristic of high ullage charges result. This source of high pressures was effectively controlled by increasing the rate of delivery of energy from the igniter."

The comments by Lamonica and Hedden (1955) also indicate that excessive ullage may be a contributing factor in generating high pressures. Later findings, however, suggested that

ullage may be used as a method for controlling maximum pressures. Obviously, tests identifying the sensitivity of the propellant to adiabatic compression need to be performed.

Although it is interesting to note that Lamonica and Hedden (1955) concluded that high pressures could be controlled by increasing the rate of delivery of energy from the igniter, it should be emphasized that too high a rate may simply result in an excessive gas generation rate, a condition which could also result in excessive pressures.

8. RELEVANCE TO ETC PROPULSION

The importance of controlling the ignition, both for controlling the IB processes and avoiding catastrophic failures, should be evident. Also of concern is the type of bulk-loaded charge used and the approach used for filling the chamber. If ullage is present, then a concern with monopropellants must exist related to adiabatic compression ignition of the bubbles. With bipropellants, some safety related ignition concerns may be alleviated. However, the use of bipropellants can result in problems with mixing of the components and less than expected ballistic performance. Bipropellants, as demonstrated by the dynamic injection work at NWC (Wood and Bryant 1977; Charters, Compton, and Wood 1977; Mallory 1981, 1984), however, offer an important approach for controlling the surface area, and they offer potentially important safety and vulnerability advantages. Slurry propellants (Goddard 1981; Goddard and Goddard 1983, 1984) may also offer a similar advantage, although the control of the IB process with slurry propellants has not been demonstrated. Dynamic injection of the propellant based on the early work at Detroit Controls (Elmore, Quinn, and Anderson 1955) might also help to stabilize the early formation of the Taylor cavity.

The importance of achieving distributed ignition, as used in solid propellant guns to reduce the effects of pressure waves, was recognized in the early BLP studies. In the 1950s, DeDapper et al. (1955) reported a concern on the use of pyrotechnic primers when located at the breech in large-caliber weapons due to the limited penetration depth of the igniter output relative to the length of the charge. He estimated that the penetration depth is less than 5 cm in 0.5 ms, a depth which was not considered acceptable for large-caliber guns. Later, Hartman et al. (1976), based on a flow visualization study, concluded that the penetration depth for an end vent type of pyrotechnic igniter mounted at the breech, would not have a

significant effect on the formation of the Taylor cavity, and, therefore, would not be an effective method for reducing the effect of pressure waves. It would, therefore, seem that approaches for achieving a more distributed ignition should be considered.

In his status report on ETC, Oberle (1988) concluded that a high level of turbulence during the IB processes would be required to generate the required surface area. The Helmholtz mixing process described above for the BLP gun is one such mechanism that can generate the required surface area.

One of the claims of the ETC system is that the IB processes can be controlled by the spatial and time dependence on the transfer of electrical energy to the plasma and to the working fluid. Although the ignition energy is much less in the BLP gun approach, we saw in one example with the relatively large solid propellant igniter (Figure 5 and Table 1) that there was an indication that not only control of the IB process may be possible with a large igniter, but also that the approach may offer a means of varying the shape of the pressure-time curve, an important consideration for possible artillery application.

The lack of control of the IB process demonstrated in Figure 6 (despite, apparently, the use of a reasonably reproducible igniter) suggests that control mechanisms during the process must extend well into combustion cycle. One approach, although not demonstrated in terms of ballistic repeatability, might be the use of slurry propellants using solid propellants to provide a well-defined surface area. Slurry propellants, however, depending on their properties, type of ignition, and particle density, could result in an increase in sensitivity (Kooker 1990). Another approach may be realized in ETC by maintaining the electrical transfer of energy during the turbulent combustion processes. Supporting the argument for a controlled transfer of energy between the primer and the BLP charge were some analytical studies (Guzdar, Rhee, and Erickson 1971) performed with the goal of understanding the wave dynamics of a breech ignited charge. These studies concluded that a primer which generated a continuously increasing pressure (i.e., a ramp-type of output) would avoid the problem of cavitation within the charge and hence avoid both ignition from adiabatic compression and the generation of uncontrolled surface areas.

Although breech ignition was shown to be feasible in the BLP gun, even for calibers up to 120-mm, it must be recognized that breech ignition will result in longitudinal waves and may very well result in unacceptable pressure amplitudes. The reason for their absence in many of the BLP tests, besides the dampening effects used with projectile base absorbers, may have been a result of uncontrolled front end ignition which may have served to attenuate the waves. This uncertainty in the BLP results serves to emphasize the importance of extensive diagnostics, especially during the early stages of a development propulsion program.

In conclusion, the control mechanisms in the BLP gun are directly related to the initial conditions. Once combustion is underway, the evolution of gas is self-sustaining. Comparing with the ETC concept and when working fluids with high activation energies are used, the evolution of gas could be limited by interaction with the plasma. If the interaction were not sufficient to sustain combustion, then the evolution of gas would cease (unlike the BLP gun case where we saw that excessive pressures may occur for cases when the propellant was poorly ignited). It would, therefore, appear that for poor ignition with the ETC concept and when working fluids with high activation energies are used, that the ignition and combustion may be fail safe, that is, excess pressures might be avoided if the working fluid were poorly ignited, or if the plasma for some reason were extinguished. The fail safe feature of the ETC gun will have to be verified by diagnostic tests.

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